Overview of nuclear forces

Brief history

- first quantitative approach: Yukawa (1935)
  - → 1π-exchange correctly describes long-range part
- later: multi-pion exchange, boson-exchange models
  - → idea: shorter range parts of nuclear forces involve exchange of "heavier particles"
    - → multiple pions ?
    - → ρ, σ^{***} meson ?

Problems: How to tell heavy mesons apart from multiple lighter mesons?

Masses and couplings unknown, fit to data

Accuracy still lacking, no consistent fundamental description

- 1960s - 1970s: QCD

⟹ fundamental theory of strong interactions based on quarks and gluons

→ two approaches emerged in 1980s

1) QCD-like models

- idea: account for quark substructure of nucleons using models based on quarks
- problem: no fundamental QCD simulation possible, crude models with weak or no connection to QCD

2) High-precision phenomenological parametrizations

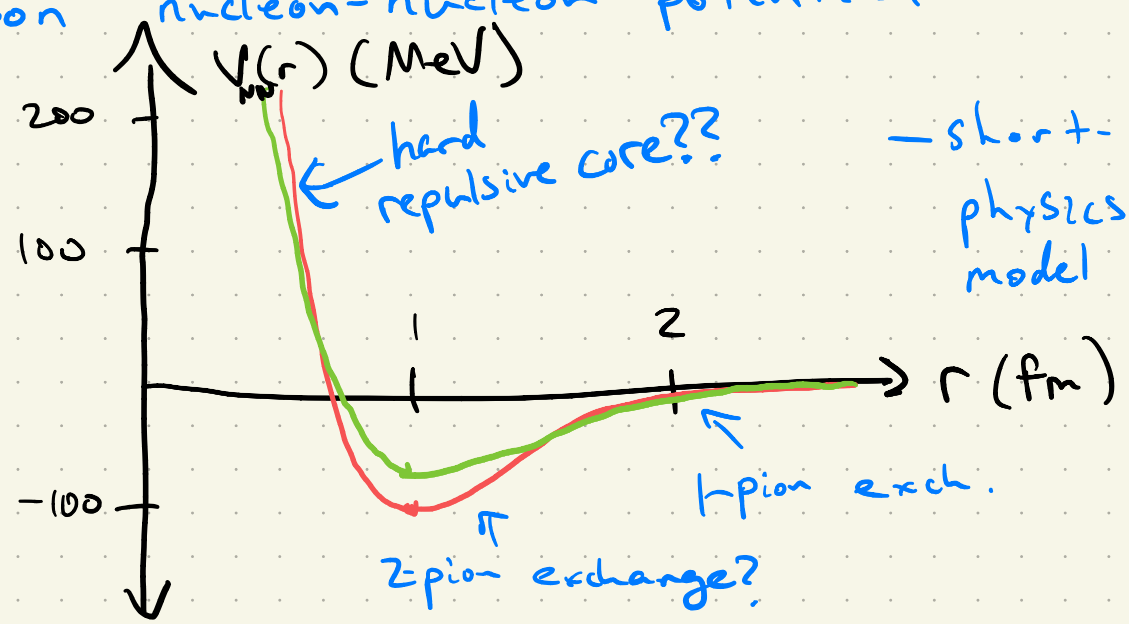
- idea: nucleons are right effective degrees of freedom, need to understand effective interactions
  (like van der Waals interactions btw atoms)
- challenge: parametrization assumed, no way to connect to QCD

- modern approach (1995+):
  - → nucleons are "efficient" low-resolution degrees of freedom
  - → can connect to QCD through effective field theories of QCD
    - Epelbaum, Hammer, Meißner, RMP (2009)
    - Machleidt, Entem, Phys. Rep. (2011)
    - Hammer, König, van Kolck, RMP (2020)
  - → can match to simulations of QCD to make true fundamental connection

⟹ union of both past approaches

Phenomenology of nuclear forces

Cartoon nucleon-nucleon potential



- short-range physics model dep.

- common assumption: V_{NN} should be local
  - → only function of $|r_1 - r_2| = r$
  - → no change r (incoming) vs r' (outgoing)

Q: Is this assumption reasonable?

Local Schrödinger equation:

$$-\frac{\hbar^2 \nabla^2}{2\mu}\psi(r) + V(r)\psi(r) = E\psi(r)$$

Nonlocal version:

$$-\frac{\hbar^2 \nabla^2}{2\mu}\psi(r) + \int d^3r' \, V(r,r')\psi(r') = E\psi(r)$$

- Local makes sense for long-range interactions

- but at short-distances, nuclei appear composite
  ("we see the structure of the nucleon")
  so interactions do not have to be local
- "short distance nuclear interactions are fuzzy

→ Form of V_{NN} may be constrained by symmetries of nature and QCD

see Okubo, Marshak, Ann. Phys. (1968)

nature $\xrightarrow[\text{e.g.}]{}$ rotational invariance

QCD $\xrightarrow[\text{e.g.}]{}$ isospin charge symmetry (approx.)

General form (ignoring isospin):

central parts:

$$V_1(\vec{r}, \vec{p}) + V_\sigma(\vec{r}, \vec{p})\, \vec{\sigma}_1 \cdot \vec{\sigma}_2$$

$$(\vec{r} = \vec{r}_1 - \vec{r}_2\,,\ \vec{p} = \vec{p}_1 - \vec{p}_2)$$

vector parts:

$$V_{LS}(\vec{r}, \vec{p})\ \vec{L} \cdot \vec{S}$$

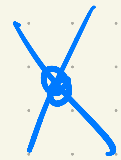
tensor parts:

$$V_T(\vec{r}, \vec{p})\ S_{12}(\hat{r})$$

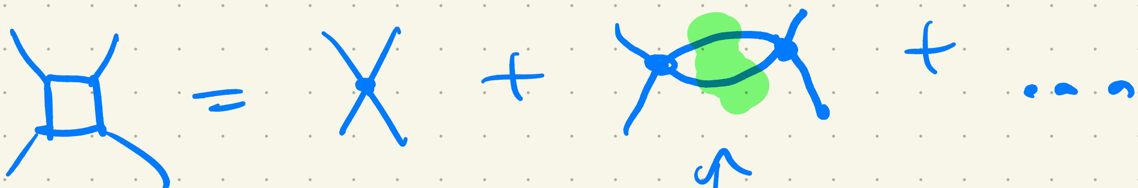
$$\left(S_{12}(\hat{r}) = \hat{r} \cdot \vec{\sigma}_1\ \hat{r} \cdot \vec{\sigma}_2 - \tfrac{1}{3} \vec{\sigma}_1 \cdot \vec{\sigma}_2 \right)$$

Nonlocality in dependence on $\vec{p}$ and in spin-orbit $\vec{L} \cdot \vec{S}$ and spin-tensor $S_{12}(\hat{r})$ operators

Effective theories for nuclear forces

- want low-energy effective theory
- cut off high-energy physics
  - → need to replace with something
- consider $V_{NN}(p, p') =$ 

Lippmann-Schwinger equation for V_{NN}



integral over momentum q

low q

= low-res. physics

→ keep

high q

looks short-range interaction

→ replace with new short-range interaction

→ if we do this right
(requires renormalization, fitting to data)
the observable NN scattering
description does not change

⇒ New equivalent low-res. potential
⇒ No longer have to care about high-
energy physics

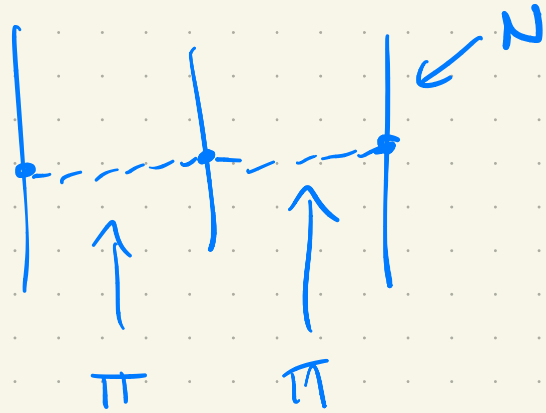
Three-nucleon forces

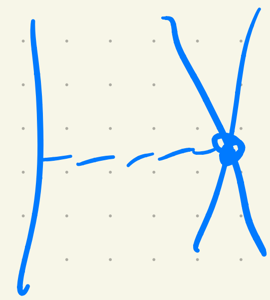
- nucleons are composite particles
- three-body forces are a natural
  occurence in such cases
- analogy: tidal forces for
  Earth, moon, sun
  → moon - Earth interaction affects
  structure of Earth (tides)
  → treating Earth, moon, sun as points
  requires three-body tidal forces

→ three-nucleon forces are <u>necessary</u>

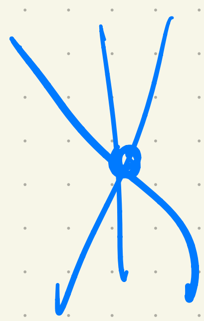
- long-range parts

e.g.





- short-range interaction



→ We will investigate impact of 3N forces in nuclei